Evaluation of Automatic Vehicle Location System Accuracy

Abstract

This study assesses the accuracy of the Automatic Vehicle Location (AVL) data provided for the buses of the Ann Arbor Transportation Authority with Global Positioning System (GPS) technology. In a sample of eighty-nine bus trips two kinds of accuracy were gauged: 1. The reported accuracy of bus locations compared to known bus stop locations; and 2. The accuracy of audio announcements relative to their corresponding stops.

The median positional error was 85 meters, ranging as high as 580 meters and as little as 3.25 meters. The frequency distribution of errors implied that some nonrandom process was leading to the errors observed. To seek to determine the nature of such nonrandom process, error patterns were examined for directional bias, but none was found. In contrast, a spatial analysis of errors showed that errors in central Ann Arbor tended to be smaller, with larger errors in outlying areas. It may be that receipt of the differential GPS correction deteriorates in outlying areas, leading to increased errors.

Most stop announcements were within acceptable distance from the bus stops to which they referred, though a small minority (fifteen percent) were triggered as close as 25 meters or as far as 450 meters from the stop. Positional error, rather than any other electronic malfunction, appeared to be behind observed in stop announcements.

Overview of AATA's Advanced Operating System

In 1997, the Ann Arbor (Michigan) Transportation Authority began deploying advanced public transportation systems (APTS) technologies in its fixed route and paratransit operations. The project's concept is the integration of a range of such technologies into a comprehensive system, termed the "Advanced Operating System" (AOS) to "smart buses", "smart travelers," and a "smart operation center" to benefit from timely and coordinated information on critical aspects of transit operation and maintenance. The prime contractor for the project was Rockwell, and providers of other integrated subsystems included: Digital Recorders Research of Triangle Park, North Carolina; Trapeze Software of Mississauga, Ontario; Prima Facie of King of Prussia, Pennsylvania; REI of Omaha, Nebraska; Red Pines Instruments of Denbigh, Ontario; and Multisystems, Inc. Cambridge, Massachusetts. Evaluator for the project was a team from the Urban and Regional Planning Program of the College of Architecture and Urban Planning, University of Michigan.

"The Smart Bus"

Central to the system is the deployment of automatic vehicle location (AVL) technology in order to provide continuous real time data on the location of transit vehicles. Each bus determines its location using global positioning satellite (GPS) technology; differential corrections are broadcast to the vehicles so they can calculate their locations within one or two meters. A Mobile Data Terminal (MDT) in each vehicle stores complete route schedules on an insertable memory card. The GPS system provides accurate time to the vehicles. Buses compare scheduled times and locations with actual locations to determine their schedule adherence. If a bus determines that it is running late, the driver is advised, and if necessary, the onboard computer notifies the Operation Center. The AVL also triggers an outside destination announcement and the internal next-stop signs and announcement. It also integrates location data with fare collection, electronic controlled engine data and ultimately, automated passenger counters,

The AATA network makes use of extensive timed transfers at four major transfer points. When a bus is running behind schedule, AOS enables digital bus-to-bus communications to improve the transfer between buses; the driver of the first bus can send a digital request (that includes the bus' location) to hold the second bus to ensure that a passenger will not miss a desired transfer.

Video surveillance is provided on board vehicles for security, as well as to help resolve any claims that may arise.

On the paratransit side, drivers receive their entire schedules and mark their arrival and departure times with date, time and location information as well as all the features above.

"The Smart Operation Center"

The AATA Operation Center collects and acts upon information provided by the transit vehicle and drivers. Each AATA bus has an 800 MHZ radio and onboard computer. The system minimizes voice transmissions by providing data messages that summarize vehicle status, operating condition, and location. Out-of-tolerance engine conditions such as oil pressure and temperature are reported in real time to the onboard computer, the Operations Center and the Maintenance Department.

Through the use of real time displays of vehicle location and schedule adherence reporting, dispatchers working at the Operation Center can manage the system and assist drivers by inserting overload vehicles in the system or recommending re-routing options. All changes to the route and schedule database are noted and automatically updated.

Onboard the vehicle, the driver has an onboard emergency system. When encountering a life-threatening situation, the driver covertly alerts the dispatcher, who immediately notes the vehicle's location on the system's center map and dials the appropriate agency. The system also allows the dispatcher to open up a central public address system inside the vehicle to monitor the situation. The system also supports responsive reporting of routine, non-life-threatening emergencies, such as passenger inconvenience.

For paratransit vehicles, reservations, scheduling, flexible integration with fixed-route, and after-trip information utilize Trapeze software. All of these elements are based on real-time information generated with the Rockwell TransitMasterTM software.

"The Smart Traveler"

The "smart travler" a person informed about his or her transportation options, as well as about current conditions relative to transit use. Inside the bus, next stop announcements, date, time and route are given to passengers utilizing the onboard public address system and a two line LED display. The driver also has the ability to trigger timed and periodic announcements for special events that can be made to support the system. Outside the bus, the current route information is announced to waiting passengers, and the destination signs are changed based upon the location.   Kiosks will provide real-time bus location information at selected locations; ultimately this information will be provided to travelers at their home or workplace via telephone, cable television or internet.

AVL Accuracy

An in depth evaluation was conducted to track or gauge accuracy, and reliability of AVL triggered events and through them the underlying AVL information. This involved sampling bus-routes, computerized data collection, statistical analysis of data, analysis using GIS techniques and generating maps. The approach used was to record the information provided by AVL and crosscheck with the known information to evaluate accuracy of the recorded information. The recorded data, a sample of which is shown in Table 1, had only the time field to the nearest second, which was matched with the every second location information in the log file (Table 2) to extract the location information (longitude and latitude) for the recorded times in table 1. After updating the recorded data with the location field, the actual location data of bus stops (Table 3) obtained from AATA was compared to it. The data were processed through GIS for spatial analysis and statistics. Similar analysis was performed to check the announcement locations as well.

Table 1. **Recorded Database**: Sample of the data recorded on the bus

Trip ID	Date	Route	Bus	Stop time	Stop ID
1	2/3/98	1	364	9:18:30 AM	2016
1	2/3/98	1	364	9:25:53 AM	1010
1	2/3/98	1	364	9:32:52 AM	1018
1	2/3/98	1	364	9:38:51 AM	1027
1	2/3/98	1	364	9:42:20 AM	2016
8	2/5/98	10	363	9:20:30 AM	1000
8	2/5/98	10	363	9:22:55 AM	1833
8	2/5/98	10	363	9:24:31 AM	1834
8	2/5/98	10	363	9:31:15 AM	1843
8	2/5/98	10	363	9:44:51 AM	2032
8	2/5/98	10	363	9:45:25 AM	2033
8	2/5/98	10	363	9:49:56 AM	1862
7	2/5/98	11	363	9:01:09 AM	1000
7	2/5/98	11	363	9:05:13 AM	1962
7	2/5/98	11	363	9:08:07 AM	1965
7	2/5/98	11	363	9:09:15 AM	1966

Table 2. **MDT Log File**: Sample of data showing every second location of a bus

Time in sec	Time	Latitude	Longitude	Adherence	Miles	Speed
35345	9:49:05 AM	42.27852	-83.74649	-5	43.92	0
35346	9:49:06 AM	42.27852	-83.74649	-5	43.92	0
35347	9:49:07 AM	42.27852	-83.74649	-5	43.92	0
35348	9:49:08 AM	42.27852	-83.74651	-5	43.92	2.1
35349	9:49:09 AM	42.27852	-83.74653	-5	43.92	3.3
35350	9:49:10 AM	42.27848	-83.74657	-5	43.92	6.5
35351	9:49:11 AM	42.27847	-83.74660	-5	43.93	6.9
35352	9:49:12 AM	42.27845	-83.74664	-5	43.93	7.3
35353	9:49:13 AM	42.27844	-83.74667	-5	43.93	7.6
35354	9:49:14 AM	42.27843	-83.74670	-5	43.93	7.3
35355	9:49:15 AM	42.27842	-83.74674	-5	43.93	6.7
35356	9:49:16 AM	42.27843	-83.74677	-5	43.93	5.3
35357	9:49:17 AM	42.27839	-83.74680	-5	43.94	5.2

Table 3. **Stoplist database**: Sample of location of actual stops provided by AATA

ID #	Lat	Long	Side	Street on	Refer	Street near
1002	42.28075	-83.74391	east side	Division St.	north of	Washington St.
1003	42.28320	-83.74371	east side	Division St.	north of	Catherine St.
1004	42.28617	-83.74353	east side	Division St.	opposite	Detroit St.
1005	42.28912	-83.73924	south side	Broadway St.	west of	Wall St.
1006	42.29038	-83.73671	south side	Broadway St.	at	Kroger Broadway
1007	42.29131	-83.73505	south side	Broadway St.	opposite	Jones Dr.
1008	42.29417	-83.72959	south side	Broadway St.	west of	Cedar Bend (past)
1009	42.29290	-83.73196	south side	Broadway St.	at	1504 Broadway (apartments on hill)
1010			south side	Broadway St.	east of	Baits Dr.
1011			south side	Broadway St.	at	Plymouth Rd.
1012	42.29934	-83.72395	north side	Plymouth Rd.	east of	Pointe Ln.
1013	42.29706	-83.73131	east side	Barton Dr.	south of	Traver Knoll Drive
1014	42.29916	-83.73250	east side	Barton Dr.	between	Traver and Barton (Northside School)
1015	42.30019	-83.73435	north side	Barton Dr.	west of	Starwick
1016	42.30141	-83.73538	east side	Pontiac Trail	north of	Starwick
1017	42.30404	-83.73502	east side	Pontiac Trail	north of	Brookside
1018	42.30765	-83.73471	north side	Arrowwood Trail	at	Pontiac Trail

Sampled data were obtained from 19 bus routes in order to capture the effect of AVL/GPS in all parts of the city that are served by AATA buses. The buses were surveyed immediately after the implementation of advanced operating systems (AOS) was completed in the first week of February, 1998.

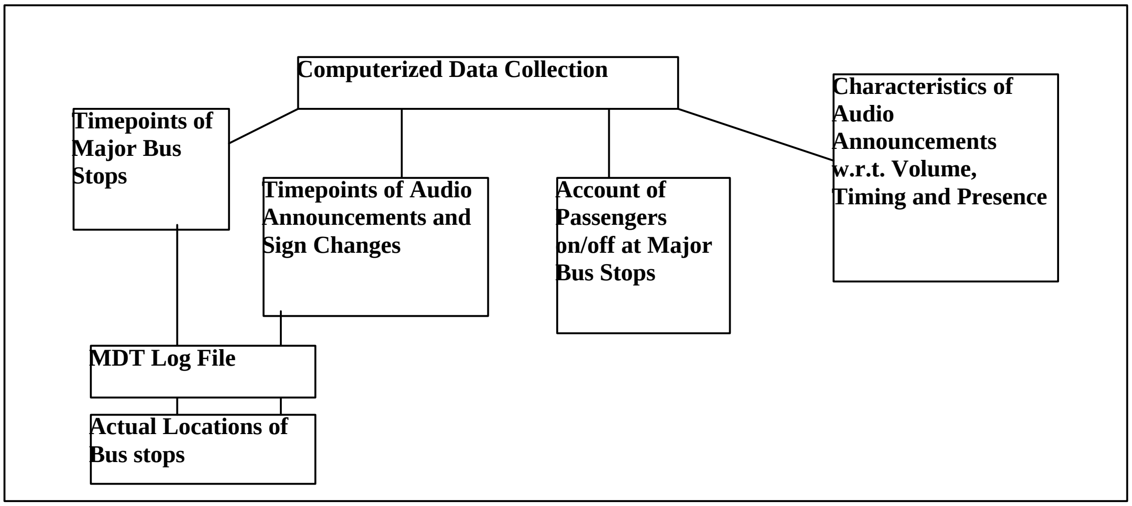

Figure 1. Computerized data collection

An electronic survey (Appendix I) was prepared that was filled by the surveyor on-board. The objective of this data collection was to collect time-point data for the announcements and stops, account for number of passengers getting on/off the bus at the major stops, and record the announcements characteristics with regard to the volume, timing, and presence. The survey was done electronically, using a laptop computer. For the collection of data (Figure 1), the surveyor rode randomly selected buses. In bearing with the intent of on-board surveys the following data were collected:

- **Time-points (to nearest second) of vehicle crossing selected identifiable locations (e.g. major intersections)**. This involved data collection from randomly selected buses as to when exactly they cross a particular intersection or identifiable point. Using a laptop computer with all identifiable locations already in the database helped ease entering of time data as and when the bus stop was reached. Once the bus stop was reached the surveyor hit the return key to enter the computer time at that stop location which was later compared with the reported time (from GPS) to determine the latitude and longitude of the location.

- **Time points of Audio Announcements and Sign Changes:** This involved collecting data as to when and where exactly the announcement and sign changes were made. This was relevant for evaluating whether or not the announcement was at the correct location, and whether the data collected was consistent.

- **Account of passenger on/off at major stops:** The number of passengers getting on and off the bus was recorded. These data would be used to evaluate the accuracy of passenger counting functions.

- **Characteristics of Audio Announcements with regard to volume, timing, and presence:** The surveyor took an account of any announcements that were not made or made at wrong time, whether the volume of the announcement was appropriate and whether the sign change accompanied audio announcements. This was to be used to qualitatively evaluate AVL various attributes relevant to the passengers and drivers.

Other Data Sets Used

A set of data was acquired from the AATA which had GPS recorded longitude and latitude information of all the current AATA bus stops (Table 3). These locations were used as actual locations of the bus stops in the analysis. All the collected and computed locations of the stops were compared with this data file. Another set of data called the 'log file' (Table 2) was obtained with the help of AATA and Rockwell. These data were extracted from the mobile data terminal of the surveyed vehicle and contained the location of the bus at every second. The location information of different vehicles on different days was compiled into one extensive data file. Throughout the analysis this file was used to extract information regarding the location of the bus.

Data processing

The time points (to the nearest second) of vehicle crossing/stopping at major stops were matched with the 'log file' to get locations of stops (locations according to the computer in the bus). These were further compared with the actual location of the stops (stoplist data) and checked for any discrepancies by calculating the 'great circle distance' (Appendix II) between the two points.

The time points (to the nearest second) of all announcements were used to obtain the distance between the announcement point and stop point (Appendix III). These distances were compared to the desired distance between announcement and stop.

The stoplist data was converted to state plane coordinates using ArcInfo. These data were displayed on Ann Arbor GIS maps to check for any discrepancies and comparisons.

Accuracy of AVL information regarding stop locations

In order to assess the positional accuracy of AVL data, the location of the bus at stops was compared to the known location of the stops from the bus location database. Because the bus does not stop precisely at the stop, a difference of up to approximately one bus length (10-15 meters) would be expected.

The analysis found typical errors considerably greater than this. The median error in location as 85 meters, with a mean of 128 meters (Figure 2, Table 4). The GPS system provides an accuracy of 100 meters for civilian use due to security reasons, yet the differential GPS in transit can be used to provide accuracy of 20 meters. Thus the observed error was considerably greater than that which might be expected theoretically. In order to examine the nature of this error, statistical, spatial, and directional analyses were performed on the data. These are described below.

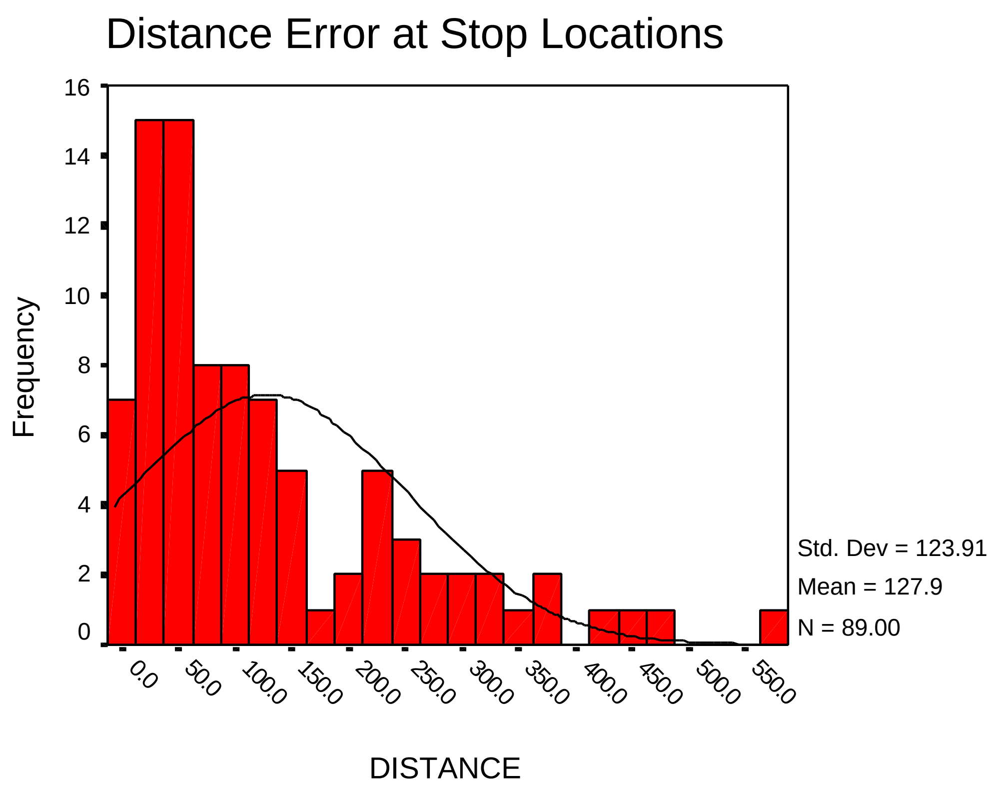

Fig.2. Frequency distribution of error at bus stop locations

Table 4. Positional Error at Stops: Summary Statistics (Meters)

N	Mean	Median	Standard Deviation	Maximum	Minimum
89	127.9	85.25	123.91	579.56	3.25

Statistical Analysis

Figure 2 shows the frequency distribution of distance error in bus locations at the stops and Table 4 gives the statistics of the data. Of the total 89 bus stops that were surveyed, half showed the stop location error of less than 85 meters. The distribution of errors may be examined to assess the processes underlying them. In particular, when error is strictly random, it is expected to be normally distributed. A normal distribution of error (given the observed standard deviation in the dataset) is displayed in the "expected" column of Table 5, while the actual observed distribution of error is displayed in the "observed value" column. The chi square statistic measures the statistical distances between the observed and expected distributions; it indicates that there is less than a 2.5% chance that such a difference would arise through chance alone. Hence this analysis suggests that there are some systematic, non-random processes underlying observed error patterns. In particular the greater than expected proportion of error excluding two standard deviations (248 meters) suggests some systematic factors occasionally combine to produce unexpectedly large errors. Furthermore, the distribution is bimodal; that is, it has two peaks, with a trough between. This distribution is suggestive of two separate processes leading to two classes of errors observed. This is discussed further below.

Table 5. Chi-square test for distribution of error at bus stops locations

Range of Error	Expected Value (%)	Observed Value (%)
(0 – 123.9 meters)	61.2.	54
(124.0 –247.8 meters)	24.3	22
(> 248 meters)	4.5	14
DF = 2; 0<p< 0.001		

Directional Analysis

This analysis was done to see if there was any bias in the location error in a particular direction that could be due to system error (GPS error). Hence, true azimuth for all longitude and latitude pairs was calculated using "geocalc" (software for geodetic calculations) and a global picture depicting error in distance and direction was created.

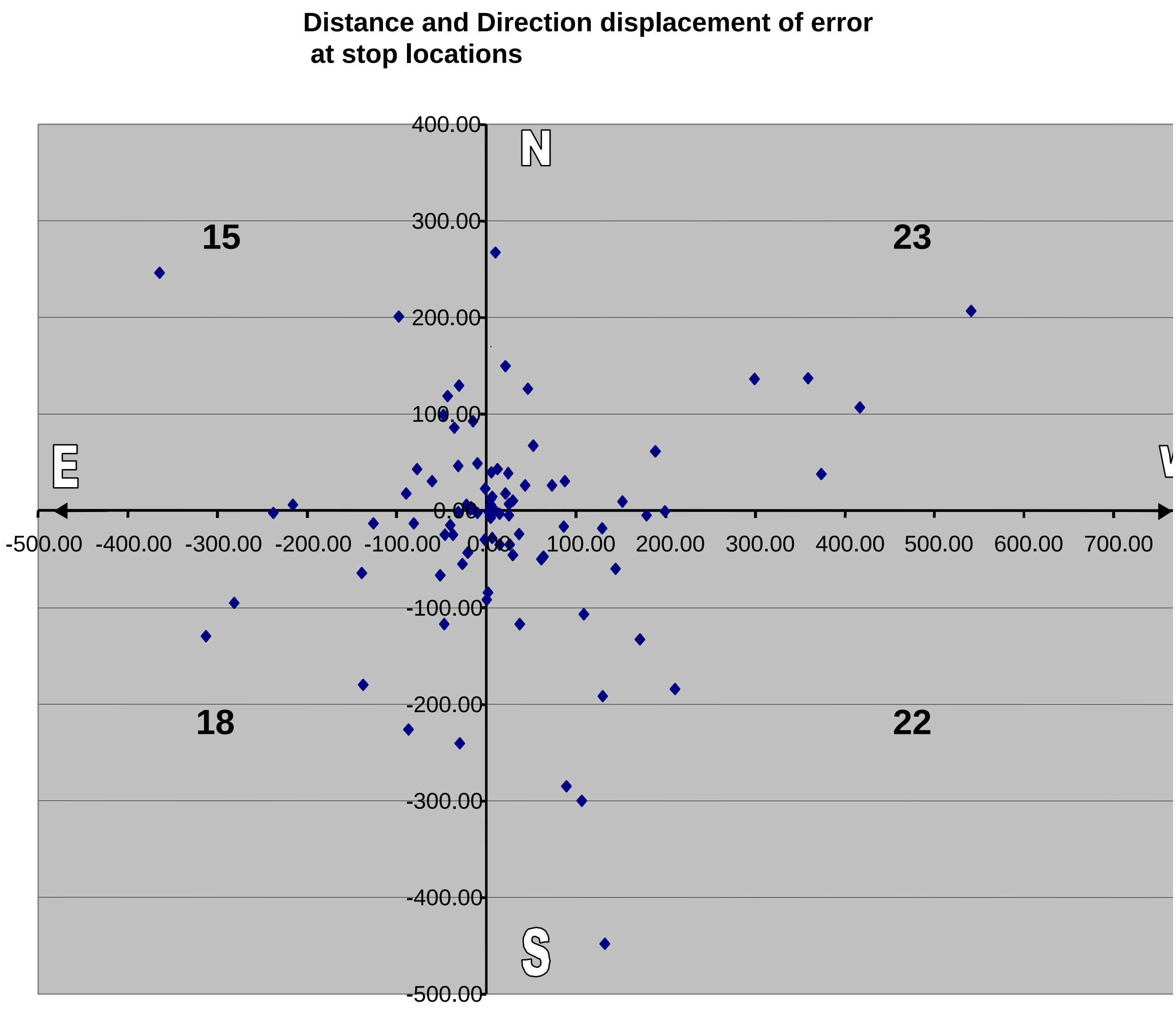

Fig.3. **Distance and direction of stop location error**

Figure 3 shows the direction and distance error from its actual location (which is taken as 0,0 here). The overall results show a random distribution of error in all directions. A chi-square test was performed to see if the distribution was random or biased in one direction (Table 6). The resultant coefficient observed was 2.1, indicating that the observed distribution was not statistically different from random in terms of the direction of error. Hence, nothing appears to be systematically biasing locational readings toward one direction or another.

Table 6. Chi-square test to verify the randomness of error distribution in bus stop locations with respect to direction.

Quadrant of error	Expected no. of errors	Observed no. of errors
NW	19.5	23
NE	19.5	15
SE	19.5	18
SW	19.5	22
DF = 3; p>0.25		

Spatial Analysis

In order to observe the error in the stop locations spatially, geographic information systems were used to map the location of the observation. This provided at a glance the association of the error with the geography of the area or the urban surroundings. Map 1 shows the actual location of bus stops vs. the recorded locations. The notion here was to see if one area of town showed more error than others and possibly to infer from this the causes of the errors of errors observed. Maps 2 and 3 show the downtown Ann Arbor and downtown Ypsilanti areas respectively. As can be observed, these areas show considerably less error than the rest of the city. Map 4 identifies two groups of error, one less than 30 meters and the other more than 100 meters.

Map 5 is a thematic map showing the distance error at stop locations. This illustration clearly shows the nearest neighbor error and identifies the local errors. Clustering of bus stops showing similar errors suggests that the geography of the area is causing the errors. The some areas on the map show the areas where local error is related or same. Table 7 shows the error at those nine stops which were observed more than once. A check of correlation (between the error at the first observation and the error at the second observation) was performed to explore the question of whether conditions at a given stop determine the error. The near perfect correlation (0.996) between errors observed at a given stop suggests that the environmental conditions, rather than random processes are leading to the error.

Table 8 shows the distance error on each bus stop of a specific route. The result shows that there is a random distribution of error. This further indicates that the error does not get compounded in a particular route as might be in the case of a dead reckoning system.

Table 7. Stops with multiple observations

Stop ID	Error 1(meters)	Error 2(meters)
2016	19.92	23.35
1000	25.61	24.67
1034	103.38	68.2
1062	0	0
1180	9.82	0
1280	5.92	0
1445	0	0
1870	419.4	446.7
1897	17.9	11.25
Pearson Correlation (r) = 0.996 (significant at 0.01 level)		

Table 8. Distance error for each stop of routes 1, 10, 11

Route 1

Stop ID	2016	1010	1018	1027	2016
Time	9:18:30 AM	9:25:53 AM	9:32:52 AM	9:38:51 AM	9:42:20 AM
Distance error	23.35	32.1	73.43	38.30	19.92

Route 10

Stop ID	1000	1833	1834	1843	2032	2033	1862
Time	9:20:30 AM	9:22:55 AM	9:24:31 AM	9:31:15 AM	9:44:51 AM	9:45:25 AM	9:49:56 AM
Distance error	25.61	65.45	276.17	0.00	32.26	110.46	0.00

Route 11

Stop ID	1000	1962	1965	1966	1811	2243	1000
Time	9:01:09 AM	9:05:13 AM	9:08:07 AM	9:09:15 AM	9:11:46 AM	9:13:33 AM	9:17:09 AM
Distance error	24.67	61.93	132.86	0.00	364.93	106.47	8.68

The spatial pattern of errors appears consistent with GPS readings receiving differential correction signals in some areas, but not in others. It may be that the greater accuracy of locational data in downtown Ann Arbor is due to more reliable receipt of differential GPS correction, while errors in the outlying areas are caused by lack of such signals. Further investigation would need to be conducted to determine if this factor is in fact behind the spatial patterns in the accuracy data observed.

Accuracy of audio announcement locations

Auditory and visual announcements are designed to be triggered at a distance of 750 feet (229 meters) from the stop that they announce. This is not to say that the stop announcement need be observed at that distance; rather its triggering at the 750 foot radius is designed to ensure that the announcement occurs sometime after that, but with ample distance from the bus stop to allow passengers time to prepare for alighting.

The distance between the announcement location and the actual bus stop were measured and compared. It was observed that half of the time the announcements occurred less than 137 meters (450 feet) from the stop. This median figure is consistent with the system's design of announcement triggering at 229 meters from the stop. Some observations appeared in unacceptable ranges, however. Twelve percent of announcements were triggered within twenty five meters of their stop, while two observations (three percent) were as far away as 450 meters from the stop they were annoucing. Figure 4 shows the frequency distribution of the distance between the announcement location and the stop and Table 9 gives the statistics of the data.

Distance between the announcement locations and actual stop locations

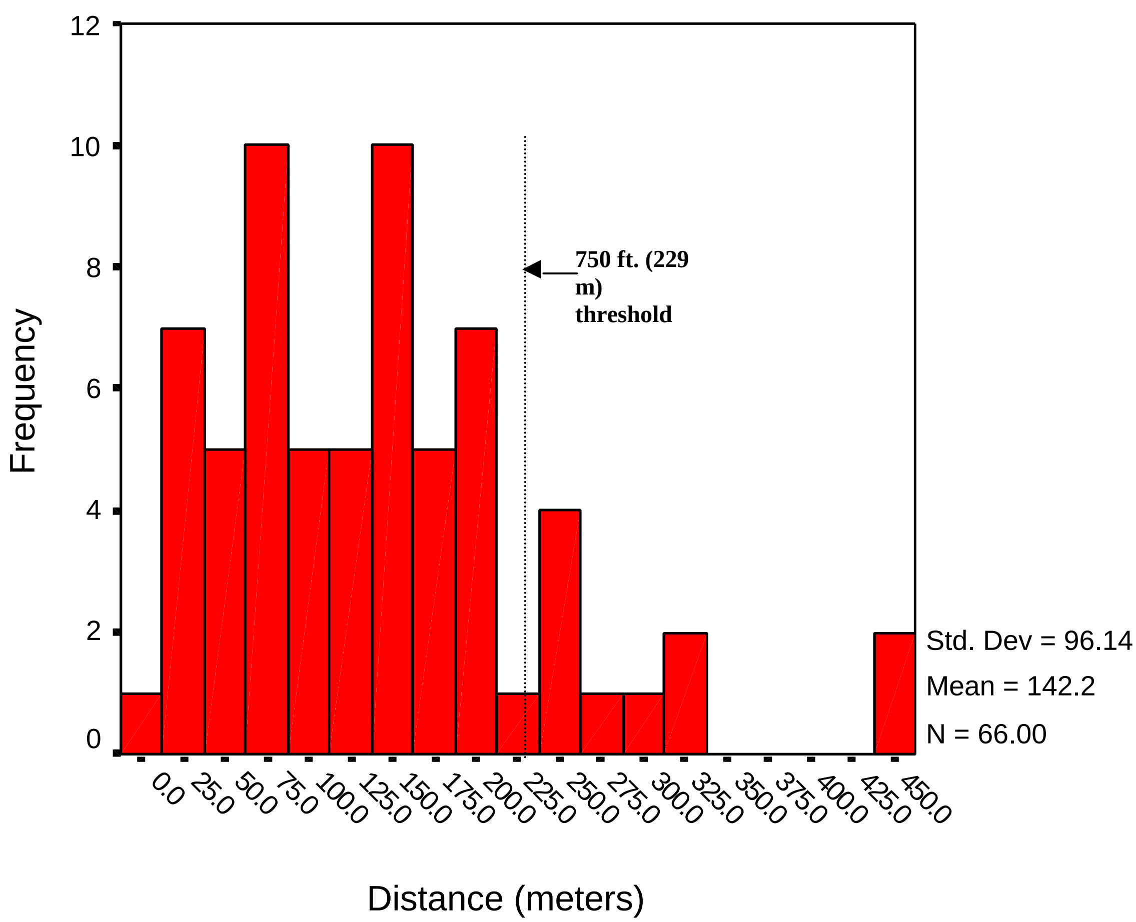

Fig.4. Frequency distribution of distance between announcement locations and actual stop locations

Table 9. Distance Between Announcement and Stop: Summary Statistics (Meters)

N	Mean	Median	Standard Deviation	Maximum	Minimum
66	142.2	137.2	96.14	451.37	4.10

Correlation Analysis

The analysis (Table 10) shows that there is a strong correlation between the distance error at stop locations and the distance between the announcement locations and actual bus stops, suggesting that error in announcement location is caused by the bus miscalculating its location, rather than other malfunctions. The correlation is significant at 0.01 level and indicates that due to the error at bus stop locations, the announcements get triggered at wrong locations i.e., too early or too late but not exactly at 750 feet from the bus stop. Figure 5 shows the correlation analysis and also displays the median and Table 11 gives the statistical details of the Part I (points lying left of the median) and Part II (points lying right of the median). It indicates that the variance increases sharply from Part I to Part II. It also shows that where error is low, there is clustering around 750 feet announcement to stop distance but where error is high, distance between announcement and stop is highly variable.

Pearson Correlation (r) = 0.778 (significant at the 0.01 level)

Table 10. Correlation Analysis: Correlation of bus stop location error and distance between announcement and bus stop location

Table 11. Comparison of variances

Correlation	Variance	St. Deviation	Mean	Median
Part I(n=33)	1189	34.5	46	38
Part II(n=32)	20383	142	268	232

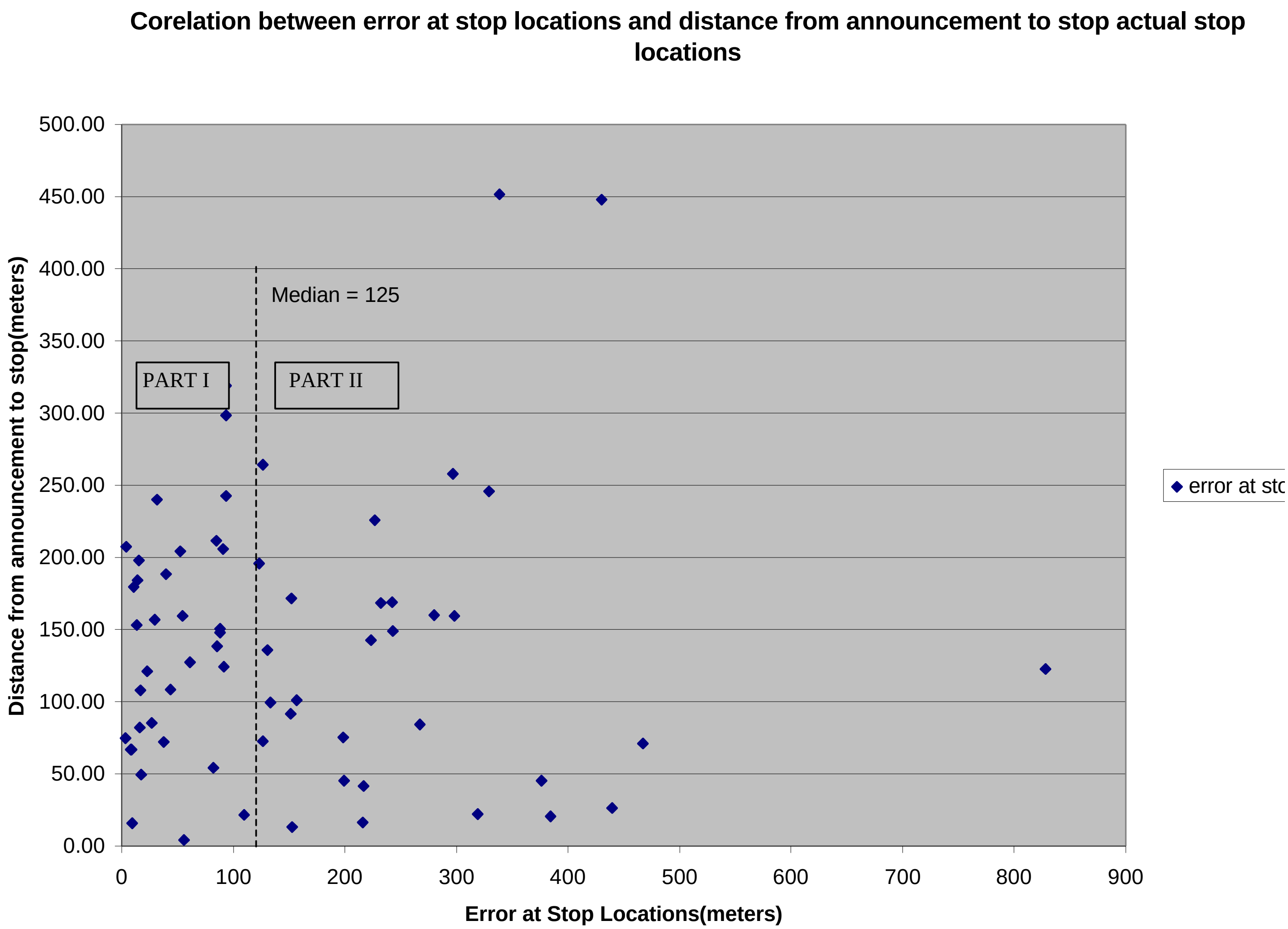

Fig.5. Correlation Analysis

Summary and Conclusions

In this research, a methodology for analyzing accuracy of AVL systems deployed by transit agencies was proposed, implemented, and analyzed. AVL systems accurately pin-points vehicle location and helps the transit agency in providing real-time and reliable information to the passengers, coordinate transfers, better schedule adherence, and thus increase ridership and reduce operating costs. The AVL accuracy study intended to highlight opportunities, goals and objectives for development and future decisions for the AATA. It explored the characteristics of AVL accuracy, pinpointed inaccuracy in announcement positions and identified sources of inaccuracy.

The overall results determine the reliability of AVL information in transit service with an accuracy of 100 meters on an average. Analysis presented suggested some systematic processes leading to non-random error. The GIS analysis showed that error was associated with location, with central areas showing greater accuracy than outlying areas. It is suggested that inconsistent receipt of the differential GPS correction in outlying areas may cause some of the large error readings in these areas.

Most stop announcements were triggered within the expected range, though a small proportion were either closer or farther than acceptable parameters. Announcement error appears to be caused by GPS positional error, as opposed to other electronic malfunctions.

APPENDIX I

SAMPLE OF ELECTRONIC SURVEY

Case 1

QA_ID ----

QB_SURV First name of the surveyor:

QC_DATE Date of survey collection:

QD_ROUTE Route on which data was collected:

QE_BUS Physical bus number:

QF_BUS Number of people on the bus at starting point:

QG_TIME Time the bus leaves the stop:

Q1_ANN 1. Time of announcement 1:

Q2_TIME 2. Time at stop 1:

Q2A_STOPID 2a.Stop 1 ID:

Q3_ON 3. Number getting on the bus:

Q4_OFF 4. Number getting off the bus:

Q5_LOC 5. Location of bus:

Q6_PRO 6. Is stop problem free?

[yes] [no]

Q7_PRESE a.Presence of announcement:

[Audio] [Audio] [Sign] [Event]

Q8_TIME b.Timing of announcements for driver and passenger:

[Too early] [Too late] [On Time]

Q9_VOL c.Volume:

[Too loud] [Too slow] [Just right]

Q11_ANN 1. Time of announcement 2:

Q12_TIME 2. Time at stop 2:

Q12A_STOPI 2a. Stop 2 ID:

Q13_ON 3. Number getting on the bus:

Q14_OFF 4. Number getting off the bus:

Q15_LOC 5. Location of bus:

Q16_PRO 6. Is stop problem free?
yes no

Q17_PRESE a.Presence of announcement:
Audio Audio Sign Event

Q18_TIME b.Timing of announcements for driver and passenger:

Too early Too late On Time

Q19_VOL c.Volume:
Too loud Too slow Just right

Q21_ANN 1. Time of announcement 3:

Q22_TIME 2. Time at stop 3:

Q22A_STOPI 2a. Stop 3 ID:

Q23_ON 3. Number getting on the bus:

Q24_OFF 4. Number getting off the bus:

Q25_LOC 5. Location of bus:

Q26_PRO 6.Is stop problem free?
yes no

Q27_PRESE a.Presence of announcement:

Audio Audio Sign Event

Q28_TIME b.Timing of announcements for driver and passenger:

Too early Too late On Time

Q29_VOL c.Volume:

Too loud Too slow Just right

Q31_ANN 1. Time of announcement 4:

Q32_TIME 2. Time at stop 4:

Q32A_STOPI 2a. Stop 4 ID:

Q33_ON 3. Number getting on the bus:

Q34_OFF 4. Number getting off the bus:

Q35_LOC 5. Location of bus:

Q36_PRO 6. Is stop problem free?

yes no

Q37_PRESE a.Presence of announcement:

Audio Audio Sign Event

Q38_TIME b.Timing of announcements for driver and passenger:

Too early Too late On Time

Q39_VOL c.Volume:

Too loud Too slow Just right